IMU Sensor-based Electronic Goniometric Glove (iSEG-Glove) for clinical finger movement analysis

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***Abstract*—Arthritis remains a disabling and painful disease, and involvement of finger joints is a major cause of disability and loss of employment. Traditional arthritis measurements require labour intensive examination by clinical staff. These manual measurements are inaccurate and open to observer variation.**

This paper presents the development and testing of a next generation wireless smart glove to facilitate the accurate measurement of finger movement through the integration of multiple IMU sensors, with bespoke controlling algorithms. Our main objective was to measure finger and thumb joint movement. These dynamic measurements will provide clinicians with a new and accurate way to measure loss of movement in patients with Rheumatoid Arthritis. Commercially available gaming gloves are not fitted with sufficient sensors for this particular application, and require calibration for each glove wearer. Unlike these state-of-the-art data gloves, the Inertial Measurement Unit (IMU) glove uses a combination of novel stretchable substrate material and 9 degree of freedom (DOF) inertial sensors in conjunction with complex data analytics to detect joint movement. Our novel iSEG-Glove requires minimal calibration and is therefore particularly suited to the healthcare environment. Inaccuracies may arise for wearers who have varying degrees of movement in their finger joints, variance in hand size or deformities. The developed glove is fitted with sensors to overcome these issues. This glove will help quantify joint stiffness and monitor patient progression during the arthritis rehabilitation process.

***Index Terms*— Data glove, wireless sensor networks, Inertial Measurement Unit, Rheumatoid Arthritis, sensor calibration**

I. Introduction

RHEUMATOID ARTHRITIS (RA) is an auto-immune disease which inflames the synovial tissue lubricating skeletal joints and is characterised by pain, swelling, stiffness and deformity. This systemic condition affects the musculoskeletal system, including bones, joints, muscles and tendons that contribute to loss of function and Range of Motion (ROM). Early identification of RA is important to initiate treatment, reduce disease activity, restrict its progression and ultimately lead to its remission. Clinical manifestations of RA can be confused with similar unrelated musculo-skeletal and muscular disorders. Identifying its tell-tale symptoms for early diagnosis has been the long-term goal of clinicians and researchers. Outcome measures such as the Disease Activity Score (DAS) and Health Assessment Questionnaire (HAQ) reflect an RA patients' disease activity and disability. These measures are partly subjective and can be influenced by other factors such as depression or unrelated non-inflammatory conditions. Traditional objective measurement of RA using the universal goniometer (UG) and visual examination of the hands is labour intensive and open to inter rater and intra-rater reliability problems.

Consequently there is a need for an objective system to record finger joint movement for analysis and detection of changes in joint ROM. This paper describes this system which combines our unique bespoke data glove with in-house developed controlling software. Focused exercise routines are designed for each patient by the clinician. Movements recorded in the clinic and at home are analysed for symptoms of stiffness severity and pain. The system could also be applied to the development of new therapies to track reduction of strength, and loss of dexterity and mobility of the hand.

II. Clinical Assessment of RA

Patients suspected to have RA are at first examined by an Occupational Therapist (OT) to quantify joint ROM and hand function. Each finger is inspected visually for the presence of Heberden and Bouchard nodes, boutonniere and swan neck deformity, and finger and thumb drift. The OT uses a UG to assess flexion, extension, adduction and abduction of the Metacarpophalangeal (MCP), Proximal Interphalangeal (PIP) and Distal Interphalangeal (DIP) joints of the fingers and thumb in degrees, and records the maximum extension and flexion range of the wrist and supination and pronation of the forearm. The DAS and HAQ are commonly used to measure disease activity and disability during clinical assessment [1]. The DAS only quantifies joints that are tender and swollen rather than the degree of pain and stiffness suffered by the patient. The HAQ is one of the most frequently used instruments for evaluation and function and widely used in clinical trials of RA [2], [3]. It assesses a patient's ability to complete activities such as dressing, cleaning eating and walking as well as pain measurement and drug therapy.

Joint Stiffness is a common condition of RA that affects their ability to perform basic activities and daily functions. Early indicators of RA derived from clinical investigations and Early Arthritis Clinics (EAC's) suggest 3 indicators for early presence of RA; early morning stiffness lasting longer than 30 minutes, swelling of more than three finger joints, and a composite compression test of small adjacent joints such as MCP [4]. Joint stiffness lasting at least an hour before maximum improvement is one of the American College of Rheumatology (ACR) criteria for RA classification [5]. Currently joint stiffness is not measured objectively in the clinical setting despite the frequent use of its duration and intensity as an outcome measurement. Joint stiffness is subjectively reported by patient recollection. Several objective measurement systems have been devised by researchers and assessed in clinical trials for effectiveness as a joint stiffness measurement device [6]–[11]. Although these research groups identified joint stiffness, uncertainties caused by rheological forces and the technical limitations of device complexity and physical dimensions restricted their uptake into the clinical setting.

III. Data gloves

Data gloves contain strategically placed sensors controlled by circuitry that communicates sensor movement to an end device. In recent years data gloves were evaluated as an effective replacement for the UG [12]–[17]. Results showed comparable repeatability to the UG with the added advantage of simultaneous angular measurement and removal of intra-tester and inter-tester reliability problems associated with the UG. Data gloves however have several drawbacks; they require laborious calibration, are difficult to donn and doff, and are designed to fit specific hand sizes and so require small, medium and large gloves to fit all hand variations. These drawbacks reduce their suitability for the clinical environment.

In this paper, our newly-designed iSEG-Glove is evaluated under laboratory conditions and compared to the state-of-the-art 5DT Ultra 14 data glove, shown in Fig. 1(c) [18] for comparison of accuracy and repeatability. Both gloves are simultaneously assessed using the Vicon Motion Capture System [19]. Both data gloves are controlled and data output is recorded and analysed using our in-house software system throughout the study. The first software iteration [20] was developed using the 5DT data glove. Once accuracy and repeatability is established, both gloves are then tested in a patient trial to evaluate their performance within a clinical environment. Results are presented for laboratory and clinical conditions in the results section.

A. *iSEG-Glove Hardware description*

The iSEG-Glove quantitatively measures ROM of each finger joint in degrees and velocity to assist medical clinicians with the accurate measurement of the common condition of loss of movement in the human hand in patients with RA. The described glove is a second generation iteration of the system designed by the authors and described in previous work [21], [22].

The iSEG-Glove shown in Fig. 1(a) is manufactured using a mix of stretchable & flexible technology. Stretchable signaling cables provide power and signal transmission between each IMU, and connect each IMU sensor back to the controlling circuitry. Fig. 1(b) shows the iSEG-Glove system integrated into its underlying cloth structure.

The glove includes 16 9-axes IMU's (each includes a 3-axis accelerometer, 3-axis gyroscope and 3-axis magnetometer) strategically placed to detect the degrees of freedom (DOF) of each finger joint of the hand. IMUs are positioned on the stretchable interconnect [23] and are located on the phalange of each finger segment to measure their orientation and biomechanical parameters.

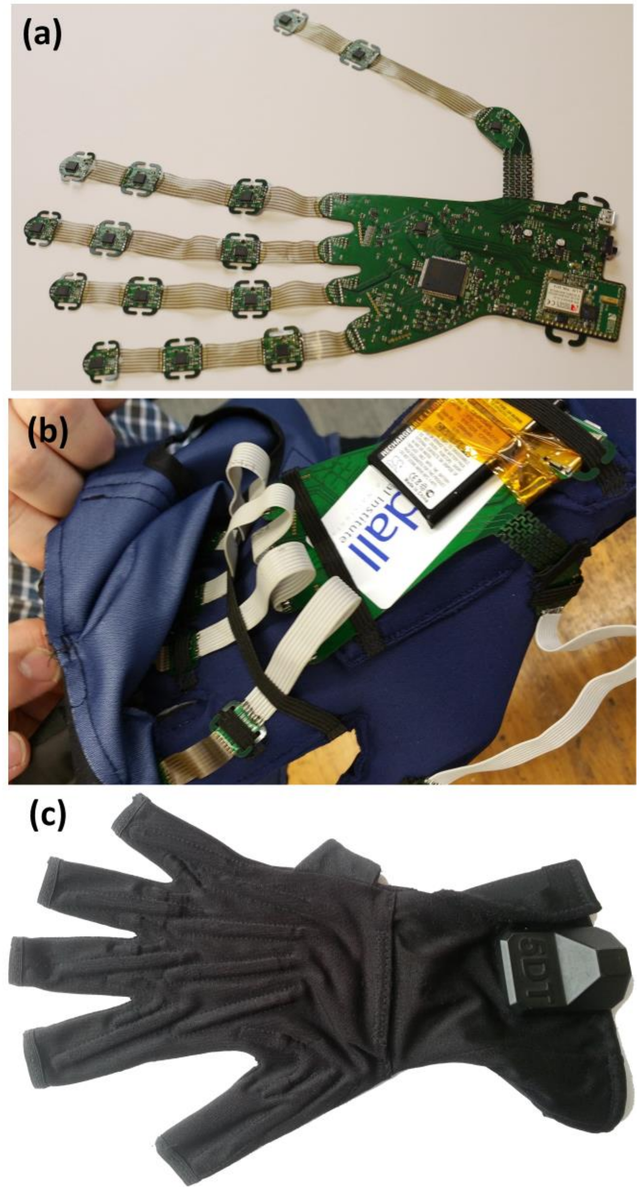

Fig. 1. (a) Configuration of the IMU data glove showing individual IMU's for each finger joint. (b) Integration of the IMU data glove into a two-layered glove structure. (c) 5DT data glove used for comparative testing.

Each IMU provides 6 DOF motion (3 translational plus 3 rotational) and 3D orientation information. By placing an IMU at both sides of each finger joint, (that is one per finger phalanx and an additional one on the palm of the hand), standard 3D positional calculations generated by each IMU is ignored and local orientation of each IMU relative to each finger joint is calculated. This orientation information is used to generate angular and velocity movement for each finger joint throughout flexion and extension exercises.

B. *Processor*

The processor selected for use in the system is an AVR32 UC3C 32 Bit Microcontroller [24]. This high performance, low power 32-bit AVR microcontroller is built as a single precision floating point unit. This particular processor is selected for its ability to execute complex embedded algorithms focused on motion analysis and development opportunity for real time low power consumption operation.

C. *Wireless communication*

The RS9110-N-11-22 [25] module shown in Fig. 2 is a IEEE 802.11b/g/n WLAN device that directly provides a wireless interface to any equipment with a UART or SPI interface for data transfer. It integrates a MAC, baseband processor, RF transceiver with power amplifier, a frequency reference, and an antenna in-hardware. It also provides all WLAN protocols and configuration functionality. A networking stack is embedded in the firmware that enables a fully self-contained 802.11n WLAN solution for a variety of applications. The module incorporates a highly integrated 2.4 GHz transceiver and power amplifier with direct conversion architecture, and an integrated frequency reference antenna. The RS9110-N-11-22 comes with flexible frameworks to enable usage in various application scenarios including high throughput and more network features.

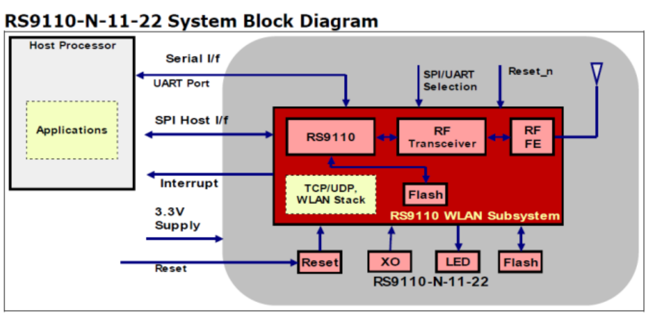

Fig. 2. RS9110-N-11-22 system block diagram [25].

The system operates according to a low complexity standard 4-wire SPI interface with the capability of operation up to a maximum clock speed of 25MHz.

The communications module conforms to IEEE 802.11b/g/n standards and includes hardware accelerated implementation of WEP 64/128-bit and AES in infrastructure and ad-hoc modes. The fact that the module supports multiple security features such as WPA/WPA2-PSK, WEP, TKIP makes it compatible with all medical ERP systems.

D. *Sensors*

The MPU-9150 [26] is a full three axis Inertial Measurement System incorporating tri-axis angular rate sensor (gyro) with sensitivity up to 131 LSBs/ degrees per second (dps) and a full-scale range of ±250, ±500, ±1000, and ±2000dps, tri-axis accelerometer with a programmable full scale range of ±2g, ±4g, ±8g and ±16g and a tri-axis compass with a full scale range of ±1200µT. The module incorporates embedded algorithms for run-time bias and compass calibration, so no user intervention is required.

The MPU-9150 features three 16-bit analog-to-digital converters (ADCs) for digitising gyroscope outputs, three 16-bit ADCs for digitising accelerometer outputs, and three 13-bit ADCs for digitising magnetometer outputs. For precision tracking of both fast and slow motions, the module features a user programmable gyroscope full-scale range of ±250, ±500, ±1000, and ±2000°/sec (dps), a user programmable accelerometer full-scale range of ±2g, ±4g, ±8g, and ±16g, and a magnetometer full-scale range of ±1200µT.

E. *Additional features*

To make the system adaptable in operation and compatible with a wide range of use cases outside the immediate application of RA monitoring, the iSEG-Glove system also incorporates optional storage via a micro SD card, battery monitoring and recharge ability, as well as a USB bootloader, USB communication interface, and the aforementioned 15 analogue inputs for optional resistive sensors (e.g. bend sensors or force sensors). The analogue front end is a buffered voltage divider to enable additional sensing functionality.

F. *System Implementation*

All the system embedded code is implemented using the Atmel Studio 6 IDE. The current iteration continuously reads sensor output and transmits the data wirelessly through a TCP socket.

Accuracy of IMU-based real time motion tracking algorithms are highly influenced by sensor sampling rate. Therefore high sensor throughput was a fundamental design requirement of the iSEG-Glove. This facilitates the development of algorithms using our in-house developed software. In addition, we intend to fully implement all movement algorithms onto the embedded platform once testing and development is completed. This eliminates the requirement for a high throughput controlling device and facilitates a low power implementation using Bluetooth Low Energy (BLE) in a future glove development.

The research team decided not to share the I2C bus between each of the gloves 16 MPU9150's, and to ensure each IMU sensor has its dedicated I2C line that are all driven in parallel. This safeguards maximum achievable sampling rates and computation times, and meets the high-speed requirements of the application scenario as specified with clinical partners regarding signal temporal granularity. Dedicated I2C lines provide the added advantage of ensuring synchronisation between all IMU sensors.

G. *Hardware Case studies*

Various scenarios were examined prior to engaging with the schematic capture and layout of the iSEG-Glove. The test setup included evaluation of the selected microcontroller, Wi-Fi module and sensors. Timing measurements were taken using an oscilloscope. Results and case studies are summarised in the following sections.

1) *Case Study 1 - Raw data transmission*

As previously described, using a wireless system to transmit raw data at the highest achievable data rate is desirable for analytical development. It is more practical to develop them using PC based software (real time or post processing) and then port them to the embedded system, than develop them directly within the data glove hardware. Table I displays timing results for Case Study 1.

TABLE I: CASE STUDY 1 TIMING ANALYSIS RESULTS

Estimated max sampling rate	~750 Hz
Processing time allocated to sample the 16 MPUs	~900 µs (600 for Acc+gyro+temperature and 300 µs for magnetometer. Note that magnetometer max sampling rate is 125 Hz)
Processing time (per sampling cycle) allocated to wireless communications	~300 µs (Tx 400 bytes: 320 data+80 extra)
Processing time (per sampling cycle) allocated to implement Quaternions	None
Processing time allocated /available to implementation of future potential drift correction algorithms	None

2) Case Study 2 - Transmission of raw sensor data

The wireless system transmits raw data and quaternions/rotation matrix from gyros at the highest achievable data rate. Quaternions are subject to drift errors and the analytics to correct these are implemented within the controlling software. We have a clear idea of the maximum processing time that could be allocated to this task. This is considered when designing firmware algorithms. Results are shown in Table II.

TABLE II: CASE STUDY 2 TIMING ANALYSIS RESULTS

Estimated Max Sampling rate	~500 Hz
Processing time allocated to sample 16 MPUs	~900 µs (600 for Acc+gyro+temperature and 300 µs for magnetometer, but note that magnetometer max sampling rate is 125 Hz)
Processing time (per sampling cycle) allocated to wireless communications	~ 420/550 µs (Q/R) (Payload 0.7/1 Kbyte: 320 data+256 /576 Q/R + 124/104 (Q/R) extra)
Processing time (per sampling cycle) allocated to implement Quaternions	~300/500 µs (Q/R)
Processing time allocated/available for implementation of future potential drift correction algorithms	None

3) Case Study 3 - Transmission of processed data

The internal sensor sampling rate should be maximised when the wireless system has full analytics embedded. In this type of scenario, a high wireless data rate may no longer be required. Results for Case Study 3 are shown in Table III.

H. IMU data glove calibration using accelerometers and gyroscopes

Data glove accuracy and repeatability is affected by the non-linear nature of glove sensor output and any misalignment between the wearers hand and data glove sensor positioning. Data glove sensor calibration improves sensor accuracy and matches the boundaries of each sensor to those of the wearer's finger joint. A calibration routine requires the glove wearer to position groups of finger joints such as MCP's and PIP's in specific poses. Each pose places a finger joint group and relevant data glove sensors at their minimum and maximum boundaries. Calibration assumes the wearer can move each finger joint to its maximum finger joint position. RA sufferers with limited joint mobility may not be capable of achieving maximum movement and make the data glove ineffective.

TABLE III: CASE STUDY 3 TIMING ANALYSIS RESULT

Estimated Max Sampling rate	100/200/250/300/400 Hz
Processing time allocated to sample the 16 MPUs	~900 µs (600 for Acc+gyro+temperature and 300 µs for magnetometer, but note that magnetometer max sampling rate is 125 Hz)
Processing time (per sampling cycle) allocated to wireless Communications	~ 420/550 µs (Q/R) (Payload 0.7/1 Kbyte: 320 data+256 /576 Q/R + 124/104 (Q/R) extra)
Processing time (per sampling cycle) allocated to implement Quaternions	~300/500 µs (Q/R)
Processing time allocated/available to the implementation of future potential drift correction algorithms	~ 8/3/2/1.33/0.5 ms (80/60/50/40/20 % of computation time) for sampling rates of 100/200/250/300/400 Hz

IMU sensors on the iSEG-Glove do not require complex calibration. IMU accelerometers placed on each one of the finger's phalanges automatically provide information on the inclination and orientation to gravity of the associated IMU within a complete sphere [27] using methods shown in Fig. 3. However, each data glove IMU sensor must detect inclination and orientation of individual finger phalanx's relative to local hand position and not to gravity. An IMU sensor placed on the back of the hand is used to subtract overall inclination of the hand relative to IMU's on each phalanx. This removes the global orientation of each IMU relative to gravity.

The slope of the wearer's fingers must be determined and removed from angular calculations. Each IMU accelerometer sensor is sampled before movement begins when the hand is in a neutral position to calculate finger joint thickness and slope offset.

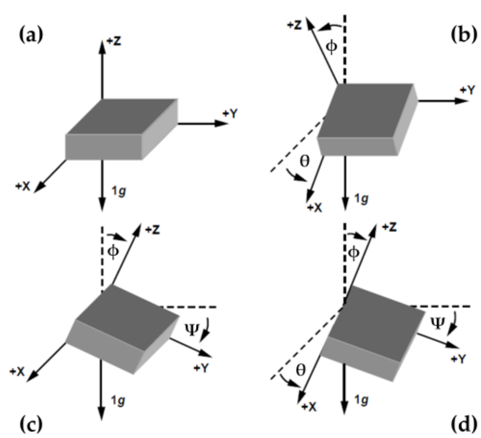

Fig. 3. 3-axis accelerometer axis information and calculation of angles for independent inclination sensing. Adapted from [27].

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The orientation to gravity of each one of the sensors placed on adjacent phalanges can be used to estimate the flexion of the finger. For example if the measured acceleration for a specific finger from the medial phalanx accelerometer is (Xout, Yout, Zout)= (-1,0,0)g and from the proximal phalanx accelerometer is (Xout, Yout, Zout)= (0,0,1)g, it indicates a flexion of the PIP joint of 90 degrees.

Each accelerometers inclination to gravity is determined according to standard formulas [27] and are shown in Fig 3b-d.

GUI / User interface

Data is streamed in real-time according to the case studies described above and post-processed by our controlling software. A pivotal role of this software is its ability to encapsulate movement limitations imposed on finger joints affected by joint stiffness. Finger joint information is captured at set times throughout each day when stiffness is most prevalent. Fig. 4 shows an example of the user interface.

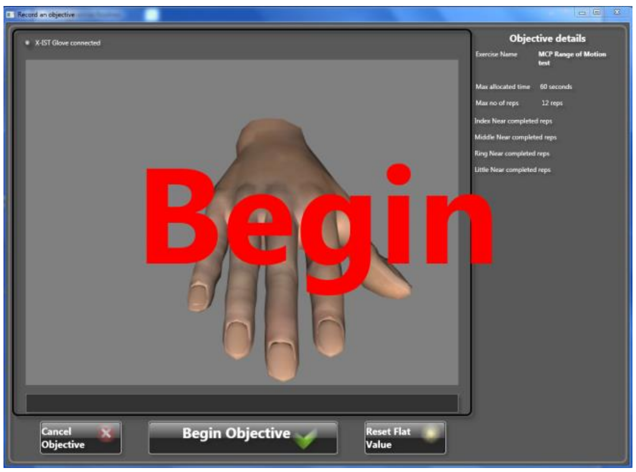

Fig. 4. Patient user interface presents the user with angular output displayed in 3D using a software model of the human hand.

Algorithms segment recorded data to extract relevant flexion and extension movement information. Fig. 5 shows one typical flexion and extension angular movement profile for a finger joint. Individual flexion and extension movement is sigmoidal shaped as demonstrated by the flexion and extension lines, and one complete open-closed hand movement produces a Gaussian shaped curve.

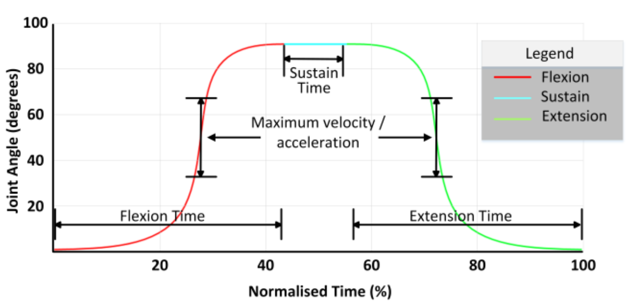

Fig. 5. Chart demonstrating segments that characterise areas of interest within flexion and extension movement.

Software analysis tools identify variations in movement throughout each recorded session and provide indicators of deterioration in movement caused by joint stiffness. Fig. 6 shows several overlaid flexion and extension movements. This information can visually indicate variation in patient movement to support the clinician during analysis of changes to patient mobility over time.

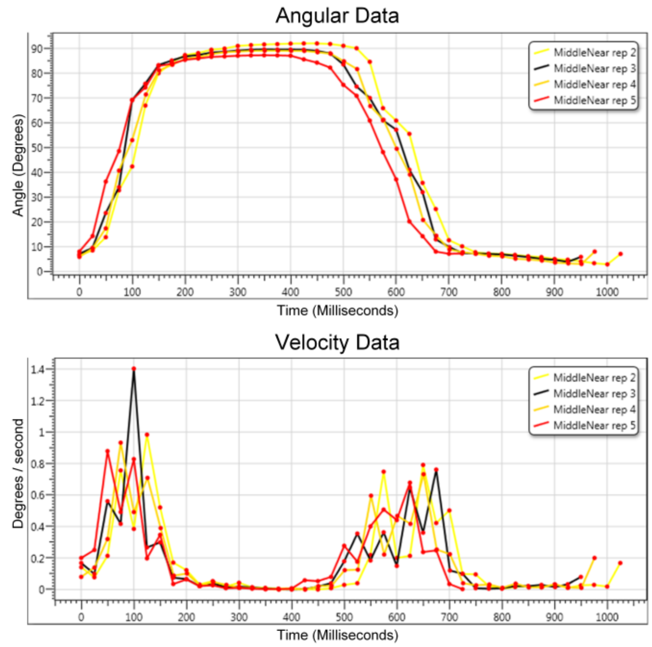

Fig. 6. Analysis of patient movement information displays graphical data for each repetition.

Each angular calculation is low-pass filtered to remove sensor noise. A complementary filter with error control is implemented to combine accelerometer output with gyroscope rotation angle, as shown in Fig. 7.

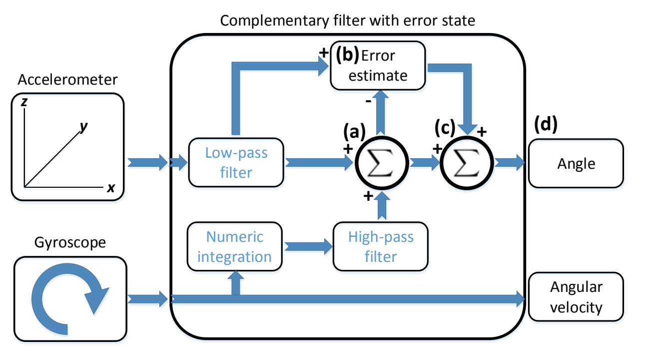

Fig. 7. Complimentary filter with error-state that is applied to IMU accelerometer and gyroscope output to remove drift.

Gyroscope rotational angle is initially accurate and drifts over time. Accelerometer angle cannot distinguish between lateral acceleration and rotation. The complementary filter acts as a high-pass and low-pass filter on both signals. It combines estimated gyroscope rotation and accelerometer angle to create an angular output.

IV. TEST RESULTS

Two testing strategies assessed accuracy and repeatability of our iSEG-Glove and the 5DT data glove. Initially we examined accuracy and repeatability for both gloves under laboratory conditions. We then examined the function of both data gloves under clinical conditions during patient trial testing. Patient testing results are presented in the next section.

Both data gloves were examined for accuracy using the Vicon MX Motion Capture System [19]. Movement was recorded by Vicon and simultaneously by our in-house developed controlling software whilst each glove was placed on blocks of wood cut to specific angles. Angular readings were assessed using Root Mean Square Error (RMS) to provide an indicator of the variance between each estimated angular repetition value and the expected true value influenced by the angle on each block of wood. RMS error is unaffected by positive and negative errors above or below the expected true angular value for each block of wood.

Repeatability testing examined the ability of each data glove to consistently replicate angular readings when the subjects hand was held in a repeatable position. Testing strategies were originally developed to assess data glove suitability as a replacement for the UG. Although no formal set of repeatability testing strategies exist, the strategies used by [17] have been adopted by subsequent research groups [12], [14], [28]–[31] and are used in this study to allow comparison between former study results and our findings.

A. Accuracy testing

Table IV shows comparison of results for the 5DT data glove and our iSEG-Glove compared with the Vicon system and the UG. Results showed the UG had greatest overall accuracy of 93.23% with overall RMS of 2.76°. This is in agreement with typical findings on goniometric accuracy with 95% of intratester reliability within 5° of measurement and intertester reliability in the range of 7° to 9° [32]–[34]. The Vicon system provided mean accuracy of 89.33% with RMS of 5.19°. This inaccuracy was most likely caused by noise, marker occlusion, and distance of reflective markers from cameras. The iSEG-Glove provided best accuracy measurement of all data gloves and demonstrated similar accuracy to the Vicon measurement system. Its RMS results showed that readings obtained from sensors contained approximately 5.95° of error.

TABLE IV: MEAN ACCURACY PERCENTAGE FOR EACH SENSOR ON EACH MEASUREMENT TECHNIQUE INCLUDING MEAN ERROR AND OVERALL ACCURACY PERCENTAGE

Sensor	Vicon	5DT	UG	IMU
Index MCP	93.31	94.20	97.95	89.57
Index PIP	91.23	92.01	90.75	91.47
Middle MCP	91.46	79.66	95.83	82.40
Middle PIP	84.08	74.97	88.96	77.29
Ring MCP	87.20	70.46	97.37	82.02
Ring PIP	86.99	91.99	90.70	89.51
Little MCP	86.14	85.83	91.28	83.38
Little PIP	94.23	74.56	93.03	86.27
Overall accuracy %	**89.33**	**82.96**	**93.23**	**85.24**
RMS	**5.19**	**7.15**	**2.76**	**5.95**

Results shown in Table IV indicate that all sensors demonstrated accuracy between 82% to 91% except for the Middle PIP sensor that had accuracy of 77.29%. Results were better than the 5DT data glove and were more impressive since the iSEG-Glove was not calibrated before use.

B. Repeatability testing

The 'flat hand' test examines each data glove's ability to maintain a minimum repeatable value after full stretch of each data glove sensor. The 'plaster mould' test examines the ability of each data glove to reproduce angular readings when positioned in a repeatable position. In all tests, the iSEG-Glove was not calibrated for the subject. The 5DT data glove was calibrated.

TABLE V: COMPARISON OF MEAN ANGULAR AND STANDARD DEVIATION (SD) READINGS RECORDED DURING 'FLAT HAND' TESTING

	5DT (Angle and SD)	IMU (Angle and SD)
Index MCP	2.34 (1.59)	-0.59 (1.87)
Index PIP	2.04 (1.05)	-2.74 (0.90)
Middle MCP	5.9 (0.55)	1.32 (2.26)
Middle PIP	3.27 (1.13)	-2.94 (1.25)
Ring MCP	5.14 (0.59)	-2.33 (1.21)
Ring PIP	1.02 (0.52)	-2.7 (1.11)
Little MCP	3.32 (0.88)	0.07 (2.56)
Little PIP	2.76 (1.32)	-1.75 (1.31)
Mean MCP	4.17 (0.90)	-0.38 (1.98)
Mean PIP	2.27 (1.0)	-2.53 (1.14)
Overall mean	3.22 (0.95)	-1.46 (1.56)

1) 'Flat hand' test results

The angle and Standard Deviation (SD) results for the 'flat hand' test are demonstrated in Table V and show the iSEG-Glove performed much better than the 5DT data glove.

2) Plaster mould test results

Table VI shows comparison results for plaster mould testing for the 5DT and our iSEG-Glove.

TABLE VI: COMPARISON OF MEAN RANGE AND STANDARD DEVIATION (SD) READINGS FROM PLASTER MOULD TESTING FOR EACH DATA GLOVE

Glove	MCP		PIP		Mean	
	Range	*SD*	*Range*	*SD*	*Range*	*SD*
5DT	8.85	2.13	6.23	2.09	7.54	2.11
IMU	5.99	1.89	5.10	1.58	5.55	1.74

Readings show the iSEG-Glove produced better repeatability for MCP and PIP joints and better overall repeatability as indicated by the lower mean range angular reading. SD readings indicate the iSEG-Glove also recorded angular values with better stability than the 5DT glove.

C. Comparison of results with previous trials

The results shown in Table VII compared angular and SD 'flat hand' and plaster mould tests for the 5DT and our iSEG-Glove with previous data glove research studies. The 5DT data glove demonstrated range readings that out-performed data glove findings by Dipietro et al. [12], and Wise et al. [17], and were similar to Gentner and Classen [28]. The data glove examined by Simone et al. [16] provided better results than all studies including the 5DT and our iSEG-Glove. However this glove contained only 5 sensors that recorded movement of the MCP joints. The iSEG-Glove performed better than all other data glove studies.

Readings recorded by earlier studies are averaged for several subjects. This can hide higher inaccurate results for individual subjects. For example, Wise et al. recorded range readings from 5 subjects that varied between 2.5° to 6.7°. Results were averaged to 4.4°. Similarly, results from 'flat hand' testing from the study by Dipietro et al. were summarised from a group of 6 male and female participants. Mean male range results went from 2.37° to 5.49° and mean female from 3.90° to 4.75°.

TABLE VII: COMPARISON OF 'FLAT HAND' AND PLASTER MOULD RANGE AND STANDARD DEVIATION (SD) TESTS WITH PREVIOUS DATA GLOVE STUDIES

Study	Flat hand test (Range and SD)	Plaster mould test (Range and SD)
Wise et al. [17]	4.4 (2.2)	6.5 (2.6)
Dipietro et al. [12]	3.84 (1.23)	7.47 (2.44)
Simone et al. [16]	1.49 (0.5)	5.22 (1.61)
Gentner and Classen [28]	2.61 (0.86)	6.09 (1.94)
5DT (this study)	2.27 (0.995)	7.54 (2.11)
IMU (this study)	4.86 (1.56)	5.55 (1.74)

V. PATIENT TRIAL RESULTS

This section describes the findings from a pilot study which examined the functionality of both data gloves when used with a group of patients diagnosed with RA.

A. Study Design

Nine patients were enrolled in an open pilot study which involved one three-hour study session per patient. Recruited patients experienced significant but not severe pain and early morning stiffness in their hands. Each patient completed a questionnaire followed by a video recording of hand flexion and extension movement. After initial glove calibration, patients worked through a protocol of finger flexion and extension exercises whilst wearing a data glove. Exercises were repeated for both gloves and recorded using our in-house software. The software provided analysis on the dynamic characteristics of movement, as described in section I. Each patient completed a questionnaire before and after using each glove on their pain and stiffness levels and at the end of the session on glove donning and doffing usability and their preference between the two gloves.

B. Inclusion criteria

Recruited patients met the following criteria: Diagnosis of RA, aged 18-80 years, glove hand size of medium when screened for glove fit.

C. Exclusion criteria

Patients were excluded if they had severe pain, swelling, loss of joint movement, hyperextension>30 degrees in any joint, broken or infected skin in the right hand, history of MRSA or Latex allergy.

D. Results

Fig. 7 shows the Coefficient of Variation (CV) readings calculated for timings for repetition movement from video recordings and movement recordings from both data gloves. CV for all subjects were very similar for video and data glove methods of recording movement, demonstrating that patient movement recorded without using a data glove is similar when each data glove was worn. CV for both data gloves were also very similar, demonstrating that both gloves measured similar timings for all subjects. CV video recording values for subject 2 were affected by the time taken to complete the first few repetitions compared to subsequent repetitions which then improved throughout remaining completed exercise routines.

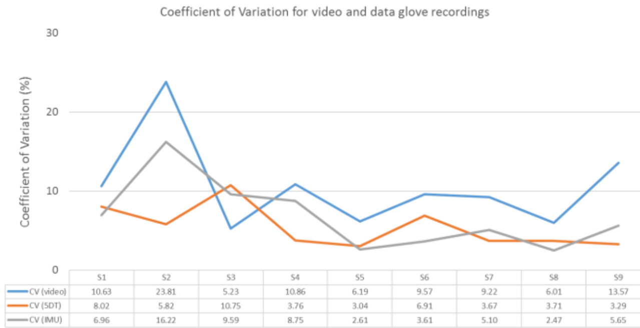

Fig. 7. CV results for recorded video and movement using both data gloves.

Table VIII shows Range and SD values for all patients generated during repeatability testing. Mean results demonstrate very similar range and SD values for both data gloves. Individual results vary.

Poor data glove fit has a negative effect on the repeatability of data glove output. This is evident in the variance in range readings for some subjects. For example, results for subject 1 showed greater repeatability for the 5DT data glove. This subject described the fit of the iSEG-Glove as too bulky and large and felt the finger sensors did not fit well with the subjects' finger joints. Correspondingly, repeatability values for subject 2 demonstrated the iSEG-Glove provided better repeatability than the 5DT data glove. This subject preferred the iSEG-Glove for fit and wearability.

Subject 4 found the 5DT data glove fitted better when compared to the iSEG-Glove. This patient commented on the outer layer of the iSEG-Glove and felt it was loose and felt bulky in comparison to the 5DT data glove. Subject 6 preferred the iSEG-Glove because of its loose fit around the right hand. This patient felt some pain.

TABLE VIII: COMPARISON OF PLASTER MOULD RANGE AND STANDARD DEVIATION (SD) REPEATABILITY TESTS FOR EACH SUBJECT

Subject	5DT		IMU	
	Range	SD	Range	SD
1	2.00	0.72	5.22	1.93
2	7.77	2.61	2.31	0.79
3	2.62	1.10	3.57	1.56
4	2.71	1.04	5.91	1.94
5	2.07	0.70	1.71	0.56
6	1.99	0.82	5.74	2.19
7	3.28	1.25	1.94	0.71
8	6.19	2.05	2.79	1.10
9	2.04	0.69	1.22	0.51
Mean	**2.41**	**1.22**	**2.42**	**1.25**

Mean results collected from the patient trial demonstrated improved Range and SD readings when compared to previous readings shown in Table VII. This is encouraging since test results were collected from patients and not under laboratory conditions.

VI. CONCLUSION

Data gloves have been proven as a viable replacement for the UG and can offer unbiased and objective finger joint ROM measurement. However their dependence on calibration reduces their usefulness in the clinical setting for use with patients who have limited joint movement.

The novel iSEG-Glove detailed in this paper removes the requirement for sensor calibration using IMU's teamed with intelligent software techniques. Test results showed our iSEG-Glove had comparable repeatability to the UG with the added advantage of simultaneous angular measurement and removal of intra-tester and inter-tester reliability. Accuracy testing results showed the iSEG-Glove provided better accuracy and less overall error than the 5DT data glove with which it was compared. Results demonstrated it had similar accuracy to the Vicon Motion Capture System.

Clinical trials provided further evidence that data gloves can be used to measure finger movement in a clinical setting. Results gathered from the patient group demonstrated similar comparison of readings recorded from a video camera and both data gloves. Repeatability results confirmed that both gloves show mean range readings that provided similar goniometric intratester reliability within 5° of measurement and intertester reliability in the range of 7° to 9°.

VII. Future Work

Feedback from patients during clinical trials demonstrated the need to reduce bulk of the iSEG-Glove skin to improve comfort and fit. The glove skin is now undergoing modifications to improve wearability.

The research team are currently examining the feasibility of whether a simplified and inexpensive data glove can be constructed with comparable accuracy and repeatability to the iSEG-Glove without associated hardware and cost complexities. A simplified data glove should meet the economical demands of healthcare providers.

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